# Remote sensing oceanography of a harmful algal bloom off the coast of southeastern Vietnam

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[1] Harmful algal blooms (HABs) in the southeastern Vietnamese coastal waters have caused large economic losses in aquacultured and wild fisheries in recent years; however, there have been few oceanographic studies on these HAB events. The present study reports an extensive HAB off southeastern Vietnamese waters during late June to July 2002 with in situ observations and analyzes the oceanographic conditions using satellite remote sensing data. The HAB had high chlorophyll *a* (Chl *a*) concentrations (up to 4.5 mg $m^{-3}$) occurring ∼200 km off the coast and ∼200 km northeast of the Mekong River mouth for a period of ∼6 weeks. The bloom was dominated by the harmful algae haptophyte *Phaeocystis* cf. *globosa* and caused a very significant mortality of aquacultured fish and other marine life. In the same period, sea surface temperature (SST) imagery showed a cold water plume extending from the coast to the open sea, and QuikScat data showed strong southwesterly winds blowing parallel to the coastline. This study indicated that the HAB was induced and supported by offshore upwelling that brings nutrients from the deep ocean to the surface and from coastal water to offshore water and that the upwelling was driven by strong wind through Ekman transport when winds were parallel to the coastline. This study demonstrated the possibility of utilizing a combination of satellite data of Chl *a*, SST, and wind velocity together with coastal bathymetric information and in situ observations to give a better understanding of the biological oceanography of HABs. *INDEX TERMS:* 4855 Oceanography: Biological and Chemical: Plankton; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 1851 Hydrology: Plant ecology; 4279 Oceanography: General: Upwelling and convergences; *KEYWORDS:* harmful algal bloom (HAB), satellite remote sensing, upwelling, SeaWiFS, chlorophyll *a*, AVHRR SST, South China Sea

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## 1. Introduction

[2] Over the past two decades, harmful algal blooms (HABs) appear to have increased in frequency, intensity, and geographic distribution worldwide [*Anderson*, 1989]. Eutrophication in estuaries and coastal waters has been considered as one of the major factors that cause HABs [*McComb*, 1995; *Smayda*, 1990]. Southeastern Vietnamese waters merge with waters of the western South China Sea (SCS), where coastal nutrients are quickly diluted. However, HABs are frequent in this region off Vietnam. Previous studies have been conducted on HAB species identification; monitoring networks have been developed to monitor the occurrence of harmful algae and algal toxins since the early 1990s [*Nguyen et al.*, 2003], but these observations were limited to only the narrow band of coastal waters. Prior to our investigations [*Tang et al.*, 2004], satellite imagery had not been used to study HABs in this region; also, there is little knowledge of the oceanographic conditions that favor the formation of HABs. In July 2002, an intensive HAB occurred in the waters off Binh Thuan Province (BTP). It caused a significant mortality of wild and aquacultured fish. The present report details our detection and observations of this HAB with analyses of ocean color satellite data, temperature, and wind data. These observations were correlated with in situ measurements. We also reviewed historical HAB records in the southeastern Vietnamese waters.

[3] Remote sensing has long been utilized for studying the distribution of algal blooms and HABs over larger spatial scales and shorter timescales than are practicable with ship-based sampling [*Tester et al.*, 1991; *Keafer and Anderson*, 1993; *Tang et al.*, 1998, 1999, 2003a, 2003b]. A winter algal bloom was observed in the southwestern Luzon Strait by using Coastal Zone Color Scanner imagery [*Tang et al.*,

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1999]. Short-time variability of phytoplankton blooms in the Arabian Sea was reported using Ocean Color and Temperature Scanner images [*Tang et al.*, 2002b]. Sea-viewing Wide Field-of-view Sensor (SeaWiFS)-derived chlorophyll a (Chl *a*) data and advanced very high resolution radiometer (AVHRR)-derived sea surface temperatures (SSTs) were also utilized to study the oceanography of phytoplankton and HAB in Hong Kong waters [*Tang et al.*, 2003a], the Gulf of Tonkin [*Tang et al.*, 2003b], the Gulf of Mexico [*Stumpf et al.*, 2003], and New Zealand waters [*Chang et al.*, 2003].

[4] In the current study, we observed an offshore algal bloom with high Chl *a* concentration in the southern Vietnamese coastal waters from late June to July 2002 when analyzing SeaWiFS images. In the same period, two field trips conducted by staff of the Institute of Oceanography, Nha Trang, Vietnam, found an intensive HAB believed to be the most serious HAB event recorded in Vietnam to date. This HAB destroyed up to 90% of the marine life in some parts of the sea off Binh Thuan Province (BTP in Figure 1b) [*Doan et al.*, 2002]. After reviewing HAB records for this area, we realized that HABs were frequent in this location. This area does not appear to receive nutrients from river discharges. What were the algal species that caused the marine life kills? Why would HABs occur frequently in this area? Why was the HAB offshore but not evident along the coast where HABs usually happen? In the present study, we examined satellite data together with in situ observations to understand the effect of the HABs. We also applied wind velocity data for a better understanding of the relationship between oceanic conditions and HAB development and transport.

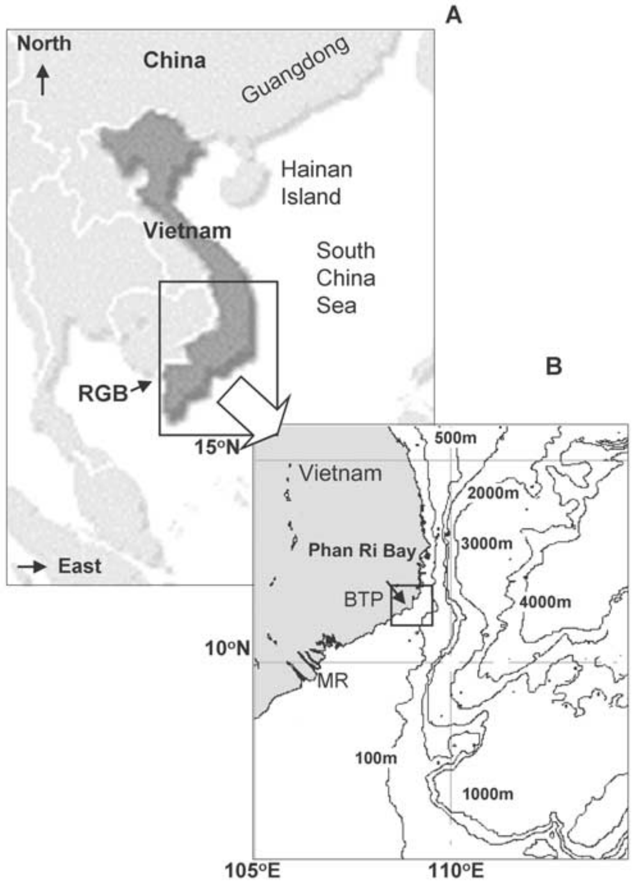


**Figure 1.** (a) Geographic location and (b) bathymetry of the study area. The small box in Figure 1b indicates the location of the HAB. BTP, Binh Thuan Province; MR, Mekong River.

## 2. Study Area, Data, and Methods

### 2.1. Study Area

[5] The SCS is a marginal sea of the west Pacific Ocean; it lies in the tropical monsoon zone between the equator and the tropic of Cancer. The seasonally reversing monsoon wind plays an important role in hydrological features and the general water circulation in the study region. The beginning of the northeast monsoon is in September; the first appearance of the southwest monsoon is in May and expands to cover the entire basin of the SCS during July and August [*Shaw and Chao*, 1994].

[6] Vietnamese marine waters are located in the western SCS with a long coastal line (Figure 1a); there is a comparatively narrow continental shelf along the coast of southeastern Vietnam, with a depth range down to 4000 m (Figure 1b). The continental slope is at its narrowest, at 2000 m and then at 4000 m depth, east of BTP (Figure 1b), where we observed HAB in June to July 2002. This region is complex in physical, chemical, and ecological characteristics.

### 2.2. Satellite Data

#### 2.2.1. SeaWiFS-Derived Chl *a*

[7] SeaWiFS-derived Chl *a* images with $1 \times 1$ km$^2$ spatial resolution were processed for the study area by using the Ocean Color 4-band algorithm [*O'Reilly et al.*, 1998, 2000] through the SeaWiFS Data Analysis System. To investigate the spatial variation of the HAB, we processed a series of images for the southeastern Vietnamese waters for June to September 2002. To investigate the temporal variation of the bloom, we selected a sampling area covering the bloom area of $50 \times 50$ km$^2$ (11.0°–11.50°N, 109°–109.50°E) and calculated the averaged Chl *a* concentrations from every image in this sampling area during June to September 2002. The total number of images was 128; the maximum number of sites in each image was 2500, but the actual number of valid sites depended on cloud, atmospheric correction error, etc.

#### 2.2.2. AVHRR SST

[8] AVHRR SST data of local coverage with $1.1 \times 1.1$ km$^2$ resolution were processed for the study area. Navigation and cloud detection techniques were applied in this study [*Emery et al.*, 1986]; cloud-free images were further processed to obtain the multichannel SST data [*Kubota*, 1994; *Simpson and Humphrey*, 1990].

#### 2.2.3. QuikScat Sea Surface Wind

[9] The microwave scatterometer SeaWinds was launched on the QuikBird satellite in June 1999. Wind velocity over the ocean surface was retrieved from measurements of the QuikScat backscattered power [*Wentz et al.*, 2001]. Weekly averaged QuikScat wind vector images were produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team (data available at http://www.ssmi.com/qscat/qscat_description.html).

### 2.3. In Situ Observation

[10] Two field trips in the Phan Ri Bay in the southeastern Vietnamese waters (11°12′N–11°19′N, 108°45′E–

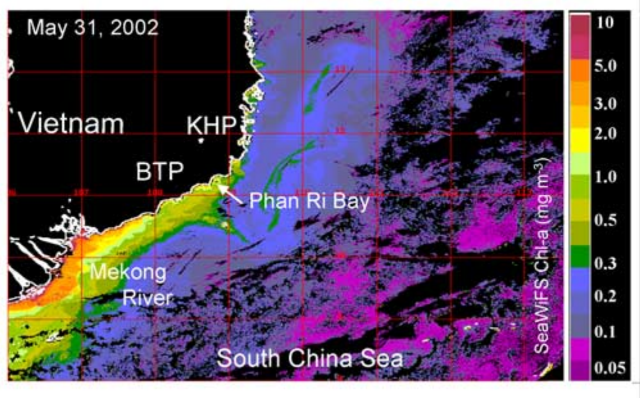


**Figure 2.** SeaWiFS image showing spatial distribution of Chl *a* in the southern Vietnamese waters on 31 May 2002. The color bar indicates Chl *a* concentrations. Land and cloud areas are marked in black. BTP, Binh Thuan Province; KHP, Khanh Hoa Province.

108°53′E) (Figure 1b) were conducted by the Institute of Oceanography, Nha Trang, Vietnam, from the middle to the end of July 2002 [*Doan et al.*, 2002]. Algal samples were taken from eight stations by conical nets with 25 μm mesh size, and 1 L of sample seawater for cell counting was taken by Niskin bottle at both surface and bottom layers.

[11] Previous observations have reported HAB events in the southwestern Vietnamese waters [*Doan et al.*, 2002; *Nguyen and Doan*, 1996; *Nguyen*, 1999; *Nguyen et al.*, 2003]. These records enabled us to compile a summary of HAB events in this region.

## 3. Results

### 3.1. Chl *a* Distributions in the Southern Vietnamese Waters

#### 3.1.1. Observation of an Algal Bloom

[12] The spatial distribution of Chl *a* concentrations in southeastern Vietnam waters was shown by a SeaWiFS Chl *a* image (Figure 2) obtained on 31 May 2002. Chl *a* concentration was relatively low (<0.1 mg m$^{-3}$) and almost uniformly distributed in the western SCS. Slightly higher Chl *a* concentrations (0.1–0.2 mg m$^{-3}$) appeared in the southeastern coastal waters of Vietnam. A Chl *a* (3–4 mg m$^{-3}$) plume was observed in the Mekong River mouth waters.

[13] In early June, the Chl *a* distribution pattern was similar to that of May, but we observed a large mass of algal bloom with high Chl *a* concentrations (up to 4.5 mg m$^{-3}$) (arrows in Figure 3b) off the coast of Binh Thuan Province (BTP in Figure 3b) in the southwestern Vietnamese waters, ~200 km northeast from the Mekong River mouth. The bloom appeared as a belt shape 50 km in width and 200 km in length from the coast toward the open ocean (arrows in Figures 3b–3e). The bloom area increased in both width and length in late July (Figure 3e) and lasted ~6 weeks. In September, this offshore algal bloom disappeared, but we observed another alongshore algal bloom off the coast of Khanh Hoa Province (KHP) (arrow in Figure 3f) to the north of BTP.

#### 3.1.2. Temporal Variation of the Algal Bloom

[14] The Chl *a* concentration (Figure 4) in the algal bloom-affected water (small black box in Figure 3e) in-

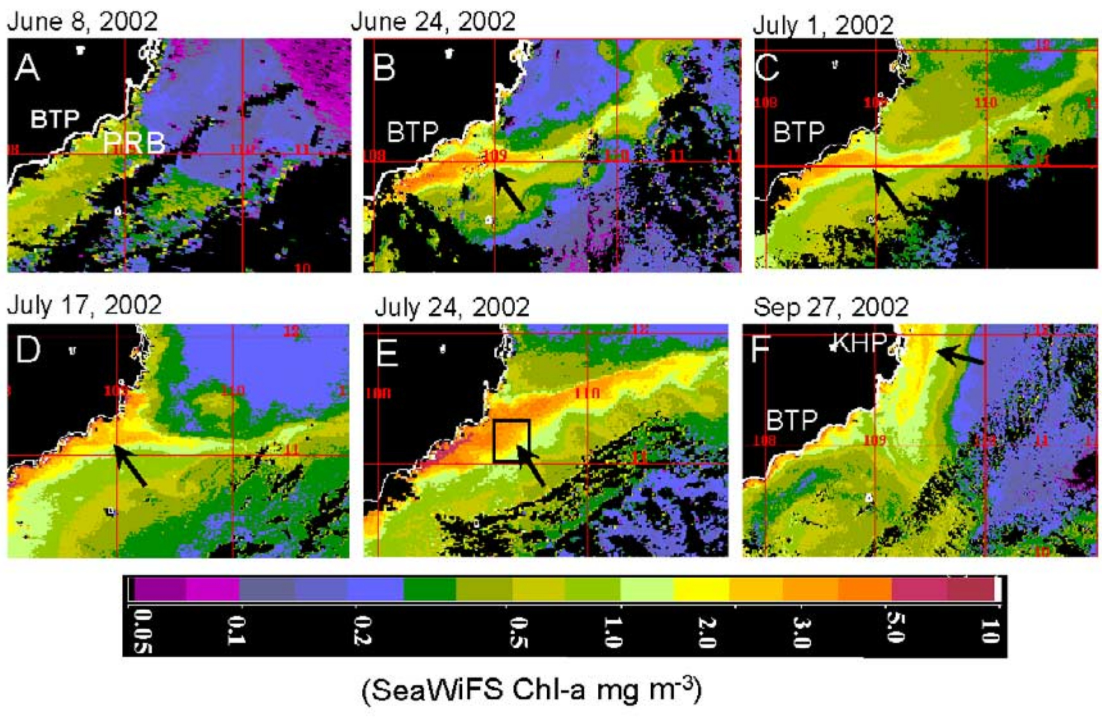


**Figure 3.** A series of snapshots of SeaWiFS-derived Chl *a* showing (arrows) an offshore HAB in the southeastern Vietnamese coastal waters in 2002. The small black box in Figure 3e indicates the location for Chl *a* sampling. PRB, Phan Ri Bay. See also Figure 2.

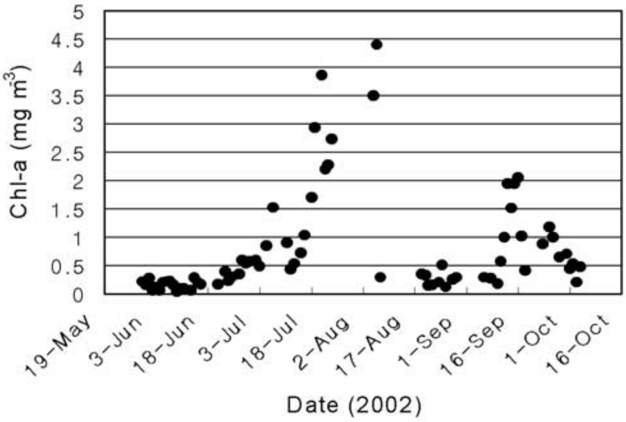


**Figure 4.** Time series of averaged Chl *a* concentrations in the HAB-affected waters (11°–11.50°N, 109°–109.5°E) (small black box in Figure 3e) showing the temporal variation of the HAB during June to October 2002.

creased in late June and reached a peak (4.5 mg $m^{-3}$) in the beginning of August and then decreased. A small peak (2.2 mg $m^{-3}$) appeared in late September; it matched the alongshore bloom that was observed in the image (Figure 3f).

### 3.2. Field Investigation of a Harmful Algal Bloom (HAB)

[15] An in situ survey confirmed this algal bloom appeared in dark green waters in the Phan Ri Bay (Figure 5a) off the southeastern coast of Vietnam in July 2002. The bloom was dominated by a harmful algal species, flagellate haptophyte *Phaeocystis* cf. *globosa* (Figure 5b) [*Doan et al.*, 2002]. The cell concentrations reached 39.5 × $10^9$ cells $L^{-1}$ and 1500 colonies $L^{-1}$, and Chl *a* concentrations reached 7.41 mg $m^{-3}$.

[16] During the bloom period, marine fauna and flora of the tidal reef were almost wiped out; losses in aquaculture were mainly in cages of lobster, grouper, and pond cultures of tiger shrimp (*Penaeus monodon*) [*Nguyen et al.*, 2003]. This HAB was the most serious marine fish kill event that had been reported in this region [*Doan et al.*, 2002; *Vietnam News*, 2002].

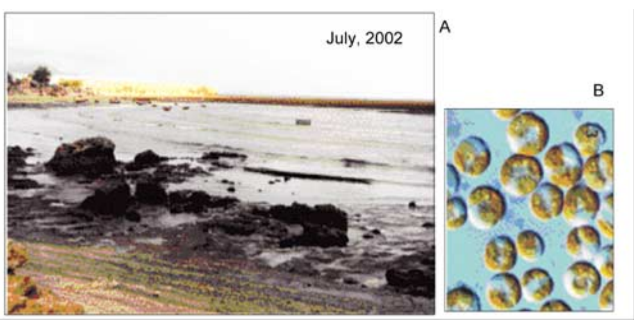


**Figure 5.** In situ observations of the HAB on 24 July 2002 in Phan Ri Bay of Binh Thuan Province (BTP in Figure 1b) coast [after *Doan et al.*, 2002]. (a) Field photo showing a HAB of the haptophyte *Phaeocystis* cf. *globosa*. (b) Microscope photo showing cells of the haptophyte *Phaeocystis* cf. *globosa* collected from Phan Ri Bay.

### 3.3. Water Temperature and Wind

[17] During the study period of July 2002, sea surface water temperatures were high (~28°C) in most waters of the western South China Sea, but we observed a low- temperature band (24°–26°C) in the southeastern Vietnamese coastal waters (black arrow in Figure 6a). This cold water band was ~200 km northeast of the Mekong River mouth and offshore toward the open sea, coinciding with the algal bloom in terms of location, shape, and timing (Figures 3b–3e).

[18] Figure 6b shows the prevailing winds in this region for the period 13–30 July. These were very strong southwesterly winds (>10 m $s^{-1}$) (Figure 6b) parallel to the coastline (1 in Figure 6b); strong southwesterly winds also appeared offshore in the western SCS (2 in Figure 6b). The wind speeds were relatively weak in the other locations in this region.

### 3.4. HAB Occurrences in the Southern Vietnamese Waters

[19] We reviewed historical HAB occurrences in the southern Vietnamese waters (Table 1) from all previous

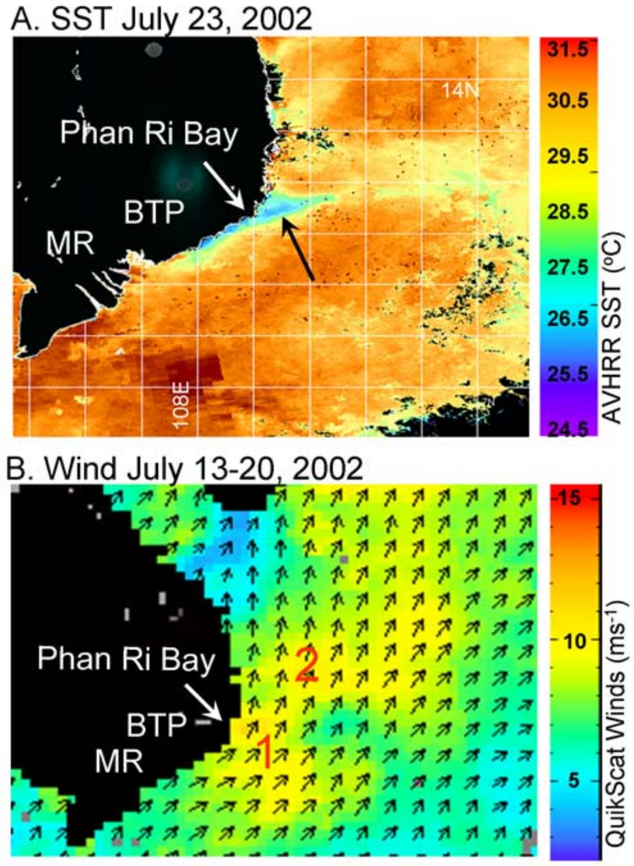


**Figure 6.** (a) Advanced very high resolution radiometer SST image showing upwelling offshore on 23 July 2002. The color bar indicates water temperature (°C). Land and cloud areas are marked in black. (b) QuikScat image of one set of weekly averaged winds (13–20 July 2002) showing strong southwesterly winds parallel to the coastline. The small arrows indicate wind directions, and the color bar indicates wind speeds (m $s^{-1}$).

**Table 1.** HAB Events in the Southern Vietnamese Waters[a]

| Event | Year | Month | Location | Species | Method |
|---|---|---|---|---|---|
| 1 | 1993 | March | Binh Thuan | *Trichodesmium erythraeum* | water sample |
| 2 | 1995 | February | Van Phong Bay | *Noctiluca scintillans* | water sample |
| 3 | 1995 | February | Cam Ranh Bay | *Noctiluca scintillans* | water sample |
| 4 | 1995 | May | Binh Thuan | *Trichodesmium erythraeum* | water sample |
| 5 | 1999 | March | Phan Ri Bay | *Trichodesmium erythraeum, T. thiebauthii* | water sample |
| 6 | 2002 | July | Phan Ri Bay | *Phaeocystis* cf. *globosa* | water sample |
| 7[b] | 2002 | July | Phan Ri Bay | *Phaeocystis* cf. *globosa* | satellite data and in situ observation |
| 8 | 2002 | July | Khanh Hoa Province | unidentified raphidophyte, *Heterosigma* sp. | water sample |
| 9 | 2002 | December | Rach Gia Bay | *Microcystis* sp. | water sample |

[a]Sources: *Doan et al.* [2002], *Nguyen and Doan* [1996], *Nguyen* [1999], *Nguyen et al.* [2003], and the present study.
[b]Present study.

available data and mapped the locations of these HABs (small open circles) in Figure 7. The first confirmed record of a HAB event was caused by the *Trichodesmium erythraeum* in Binh Thuan water in 1993 [*Nguyen and Doan*, 1996]. The actual number of HAB events may be quite high according to the observations of the local fisherman, but the scientific records are still few [*Nguyen et al.*, 2003]. We noticed that most HAB events had been observed along the southeastern coastal waters offshore of BTP and KHP, the same location where we report that a HAB occurred in July 2002 in the present study.

## 4. Discussion

### 4.1. Harmful Algal Blooms

[20] Our study revealed an offshore HAB in the southeastern Vietnamese waters in July 2002. The bloom in July 2002 was dominated by *Phaeocystis globosa* and lasted for ~6 weeks. This species *Phaeocystis* cf. *globosa* also caused an extensive HAB in southeast China coastal water (Fujian and Guangdong Provinces, Figure 1a) in late autumn 1997; the direct market value loss in seafood was ~8 million U.S. dollars [*Lu and Huang*, 1999]. A large spring *Phaeocystis globosa* bloom occurred in 2001 at the entrance of nearby saltwater Lake Grevelingen; its cell concentrations reached between 30 and 50 $\times$ $10^6$ $L^{-1}$, and it lasted for several weeks [*Peperzak et al.*, 2002]. We do not have hydrographic knowledge and ecological data for these algal blooms.

[21] The marine alga *Phaeocystis globosa* has been commonly reported from coastal and oceanic temperate waters [*Baumann et al.*, 1994; *Moestrup and Thomsen*, 2003]. This species has not been considered as a toxin producer; however, it may be regarded as a suspect species because its relative, *P. pouchetii*, has been thought to produce unknown toxic compounds that are responsible for fish kills [*Eilertsen and Raa*, 1995]. It is obviously a HAB species, especially in this study. The main observed adverse effects of *Phaeocystis* are clogging of fish nets, killing fish, and causing foams to form over adjacent beaches [*Moestrup and Thomsen*, 2003]; this species of alga may produce acrylic acid, which is harmful to marine organisms. High algal cell concentrations may also reduce oxygen levels in the water, and that could cause fish kills. Further research is needed to explain the precise causes of the fish kills.

### 4.2. Nutrients and HAB

[22] Our results also indicated that HABs were frequent off the southeastern Vietnamese waters in summer (Table 1 and Figure 7). Algal blooms usually occur for a suite of reasons, such as the availability of nutrients, suitable water temperature, sufficient light, stable water column, and the algal and protozoan species in an area. The study area is off southeastern Vietnam, where the general characteristics are of tropical mesotrophic waters, receiving relatively high energy from solar radiation. In these waters, temperature and light are not limiting factors for phytoplankton growth, but nutrients are important factors [*An and Du*, 2000; *Tang et al.*, 2003b]. In our study, the location of the HABs faced the open sea and was ~200 km from the Mekong River mouth where nutrients discharged from the river would be expected to be readily diluted. What was the source of nutrients causing the offshore HAB that lasted ~6 weeks? Although the specific condition that triggers the HAB is difficult to specify and to differentiate, we can identify some important factors from this study.

[23] In July, SSTs are usually high because the water column is stratified. The low-SST band (Figure 6a) may suggest strong upwelling waters offshore. When the strong winds were parallel to the coastline (Figure 3b), where the slope of the continental shelf was steepest down to a depth of 2000 m (Figure 1b), the offshore Ekman transport drew up the deep cool waters from the ocean bottom. As such, it induced a cross-shore upwelling (Figure 5a). Meanwhile, a separation of flow may also deliver nutrients and phytoplankton from the Mekong River mouth northeast to the HAB. This theory merits further detailed study.

[24] Upwelling can bring nutrients from deep waters to surface waters, and these nutrients can then support phyto-

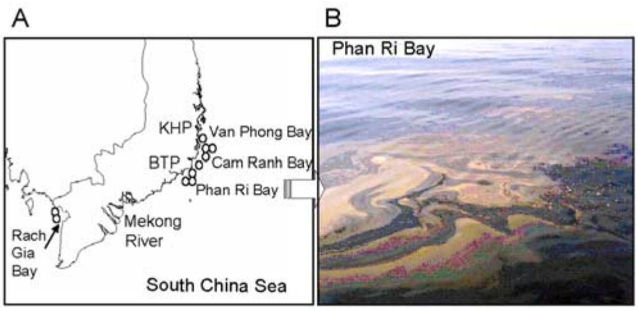


**Figure 7.** (a) Map showing bay areas in the southeastern Vietnamese waters. Open circles indicate the locations of historic records of HAB events during 1993–2003 (Table 1). Phan Ri Bay is the location where we observed a HAB in July 2002. (b) HAB of *Trichodesmium erythraeum* in Phan Ri Bay in April 1999 [after *Doan et al.*, 2002].

plankton blooms [*Ryther*, 1969; *Tang et al.*, 1999, 2002a, 2003b] in a continuous way if the right wind conditions persist. Thus these upwelling-induced algal blooms may occur offshore and may be maintained for long periods. The upwelling along the western SCS was observed in previous studies [*Wyrtki*, 1961; *Ho et al.*, 2000; *Kuo et al.*, 2000]. A similar mechanism linking shellfish toxicity to changes in upwelling conditions was reported for the northwest coast of Spain [*Fraga et al.*, 1988]. In our study area, upwelling may often be prevalent in the southwesterly monsoon and induce phytoplankton blooms [*Tang et al.*, 2004]. However, most of the blooms may not be HABs; therefore their presence would not have adverse impact on fisheries, and they would not be recorded.

### 4.3. Remote Sensing and Field Observations

[25] Satellite remote sensing data have been analyzed for algal bloom studies in the northern SCS [*Tang et al.*, 2003a] and northern Vietnamese waters [*Tang et al.*, 2003b]. In some waters, particularly in case II water, the satellite-derived Chl *a* value may be adversely affected by suspended material (SSM) or by colored dissolved organic matter (CDOM) [*Sathyendranath*, 2000]. Our study area featured a steep near-coastal continental shelf facing the open sea where the influence of SSM and CDOM was relatively limited. SeaWiFS-derived Chl *a* values fit well with the in situ measurements in the western South China Sea, except in river mouth waters [*Tang et al.*, 2003b, 2004]. One SeaWiFS image also indicated another phytoplankton bloom off the KHP waters (arrow in Figure 3f). This bloom was in the same area as a reported HAB caused by an unidentified species of raphidophyte, *Heterosigma* sp., along the KHP coastal waters (event 8 in Table 1). This HAB caused mortality in aquacultured tiger shrimps in ponds in KHP [*Nguyen et al.*, 2003]. A field survey also observed another HAB caused by *Trichodesmium erythraeun* in 1999 in Phan Ri Bay of BTP (Figure 7b and event 5 in Table 1), where Chl *a* concentrations reached high levels.

[26] In the present study, SeaWiFS-derived Chl *a* images provided information on spatial and temporal variations of a HAB process. In addition, the combination of satellite data of Chl *a*, SST, and wind velocity together with in situ observations helped us to understand the oceanographic mechanisms of the HAB offshore of the southeastern Vietnam waters.

## 5. Conclusions

[27] By analyzing SeaWiFS-derived Chl *a* images and other oceanic data we observed an extensive HAB caused by haptophyte *Phaeocystis* cf. *globosa* off the coast of southeastern Vietnam in July 2002. This HAB was offshore and lasted for ~6 weeks. The results support the postulate that the HAB was induced and supported by upwelling nutrients that were driven by southwesterly winds. Further investigation is needed to understand why only this particular algal species bloomed but not other algae.

[28] This study also revealed local knowledge that algal blooms were frequent in the southeastern Vietnamese waters and provided scientific evidence that such blooms may be associated with the upwelling occurrences in this region. It suggested that upwelling events as sources of nutrients were among the most significant nutrient enrichment phenomena, along with eutrophication and river discharge, for inducing HABs in these off-coastal waters.

[29] The present study demonstrated that SeaWiFS images can help in tracing the spatial and temporal process of HAB events; the combination of remote sensing data of Chl *a*, SST, and wind together with a knowledge of coastal continental shelf bathymetry and in situ observations can be very helpful for understanding the biological oceanography of HABs.

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